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A NOVEL METHOD FOR MEASUREMENT OF TOTAL HEMISPHERICAL EMISSIVITY (PREPRINT)

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14. ABSTRACT
This report was developed under a SBIR contract. This paper describes a heat flux-based method for measuring emissivity of a surface. In this method the emissivity of a surface is calculated using direct measurement of the heat flux passing through the surface. Unlike storage-based calorimetric methods, this method does not require application of known amounts of heat to the surface or the temperature history of a known amount of thermal mass to calculate the surface emissivity. Application and operation of this method is much simpler than calorimetric methods as it does not require careful thermal insulation of the heat radiating body from the surroundings. This technique allows emissivity measurements of the newly developed variable emissivity surfaces with significantly lighter and energy efficient measurement equipment that can operate for long term space missions. In this study, a commercially available thermopile heat flux sensor was used to measure the emissivity of a black paint and a variable emissivity surface, Electrostatic Switched Radiator (ESR). This paper details the concept, experimental setup, and the experiment results.

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A Novel Method for Measurement of Total Hemispherical Emissivity

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Abstract. This paper describes a heat flux-based method for measuring emissivity of a surface. In this method the emissivity of a surface is calculated using direct measurement of the heat flux passing through the surface. Unlike storage-based calorimetric methods, this method does not require application of known amounts of heat to the surface or the temperature history of a known amount of thermal mass to calculate the surface emissivity. Application and operation of this method is much simpler than calorimetric methods as it does not require careful thermal insulation of the heat radiating body from the surroundings. This technique allows emissivity measurements of the newly developed variable emissivity surfaces with significantly lighter and energy efficient measurement equipment that can operate for long term space missions. In this study, a commercially available thermopile heat flux sensor was used to measure the emissivity of a black paint and a variable emissivity surface, Electrostatic Switched Radiator (ESR). This paper details the concept, experimental setup, and the experiment results.

Nomenclature

T	=	temperature (K)
ε	=	emissivity
σ	=	Stephan-Boltzmann constant
q''	=	heat flux (W/m^2)

Subscripts:

s	=	surface
∞	=	far-field

Introduction

RECENT developments in variable emissivity surfaces and need for their testing in space environments have generated a demand for emissivity measurement equipment that is lighter, more efficient, and less complex than the conventional emissivity measurement techniques. Unlike traditional constant emissivity surfaces such as paints and films, the new variable emissivity surfaces are more complex in structure and performance. Variable emissivity surfaces can be classified as either changing the optical properties of the surface material itself or modifying the surface structurally to alter its radiation heat transfer performance. Polymer-based materials[1] and inorganic thin films[2] are two examples of the surfaces with variable optical properties. Two structurally active surfaces under development are electrostatic devices[3, 4] (also called Electrostatic Switched Radiator (ESR)) and MEMS louvers.[5]

ESR operates by opening and closing a gap between two surface layers, with the gap hindering heat transfer through the surface layers. The MEMS louvers are microfabricated versions of the larger scale louvers that were developed earlier for spacecraft. The acceptance of these active thermal control systems requires a demonstration of their performance in the relevant space environment.

The most common methods in use for measuring the emissivity of a surface are calorimetric and optical measurement methods. Calorimetric method involves measuring the heat power delivered to the test sample as well as the temperatures of the emitting surface (the sample) and the absorbing surfaces in a vacuum over time. A heat balance analysis is then used to determine the emissivity. This requires that the sample be well insulated on the sides and back so that the only heat transfer is through the surface whose emissivity is being measured. Optical techniques involve illuminating a sample with infrared energy and measuring the percentage of energy reflected from the surface. The absorptance is calculated from the reflectance and then used to calculate normal emittance by Kirchhoff's Law and the Stephan-Boltzmann equation. The optical method is generally less labor-intensive than the calorimetric method, but in order to accurately obtain a hemispherical emissivity the same measurements must be repeated at all angles and then numerically integrated. In many cases this is not practiced and the normal emissivity is considered as an approximation of the hemispherical emissivity. Although in a lab environment the complexity of measuring emissivity of the spatially and temporally variable emissivity surfaces could be overcome using sophisticated testing equipment designed based on the conventional emissivity measurement techniques, the application of such systems in space is associated with a significant weight, energy consumption, and data volume.

The advantage of the Heat-Flux Based (HFB) method is that it measures the hemispherical emissivity without the need for careful thermal isolation of the test surface/structure. The HFB method can measure spatial variations of emissivity without requiring the complexity and labor-intensity of the optical method. Thus it combines the major advantages of each previously used technique. Furthermore, HFB method provides real-time measurement of the surface emissivity through direct measurement of heat flow through the emitting surface. The HFB method requires the minimum volume of data measurements and processing. The heat flux passed through the surface, the surface temperature, and the ambient temperature are the only information required to calculate the surface emissivity. This method requires neither the temperature history nor thermal isolation of the structure on which the variable emissivity surface is installed. In addition to its simplicity and significantly reduced data volume, the HFB emissivity measurement method eliminates the need for heaters and their power measurement equipment, control

system, and more importantly heating energy that is at premium in any space mission. The HFB method can measure the emissivity of an active surface such as an ESR while it is operating as part of the space vehicle thermal control system.

In HFB method, the heat flux through the emitting surface is directly measured using one or more (depending on the required spatial resolution) heat flux sensors that are directly incorporated between the active (or passive) surface and the structure on which the surface is installed. The low thermal capacitance of the available heat flux sensors can provide good temporal resolution of the heat flux. The small size of the sensors allows the necessary spatial resolution to resolve the performance of a spatially variable emissivity surface. The HFB method also allows multiple surfaces with different emissivities to be tested simultaneously. The objective of this work is to demonstrate the capability of the HFB method in measuring the emissivity of passive and active surfaces. The passive surface used in this study is a black paint and the active surface is ESR (manufactured by Sensortex, Inc.). At the end of this paper, an overall view of an under preparation space experiment that incorporates the HFB emissivity measurement method is discussed.

Heat Flux-Based Emissivity Measurement

In HFB method, a heat flux sensor is installed underneath the surface of the structure whose emissivity is being measured. Figure 1 shows the schematic of this configuration.
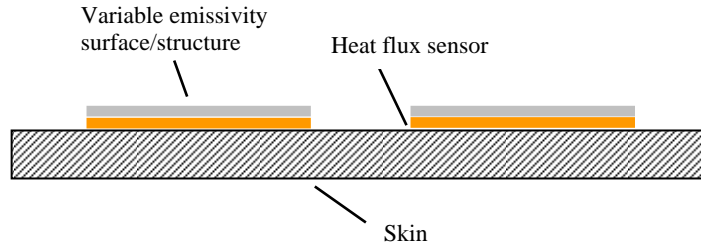

Fig. 1 Schematic depicting the arrangement of heat flux sensors with respect to emitting surface.

The heat emitted from the surface passes through the heat flux sensor. Knowing the heat flux through the sensor, the total hemispherical emissivity of the surface can be calculated using the Stephan-Boltzmann law of radiation:

$$\varepsilon = \frac{q^{''}}{\sigma\left(T_s^4 - T_\infty^4\right)} \tag{1}$$

It should be noted that the direct measurement of the heat flux through the gauge makes the parasitic heat loss/gain irrelevant to the measurement of emissivity since any parasitic heat paths simply change the surface temperature, which is measured anyway.

In this study, two different sizes of heat flux sensors were used. Both sensors (shown in Fig. 2) are fabricated by RdF Corporation. They consist of many thermocouple pairs deposited on either side of a thin polyimide film and arranged to form a thermopile. Heat passing through the gauge produces a temperature difference across the film resulting in an EMF at the output leads. First, a standard heat flux sensor (RDF 27160) was used to demonstrate the capability of the HFB method in measuring the emissivity of a passive coating (black paint). Second, a larger heat flux sensor was custom made to accommodate the size of an ESR device. The size of the standard sensor is 11.9 mm $\times$ 46.2 mm and the size of the custom made sensor is 50.8 mm $\times$ 50.8 mm. The average nominal sensitivity of the RDF 27160 is 0.92 $\mu V/(W/m^2)$ at 25 °C and the sensitivity of the large sensor is 6.499 $\mu V/(W/m^2)$. This value is temperature-dependent; the temperature correction factors are available from the manufacturer. The sensors are calibrated by the manufacturer with an uncertainty of less than 5%.
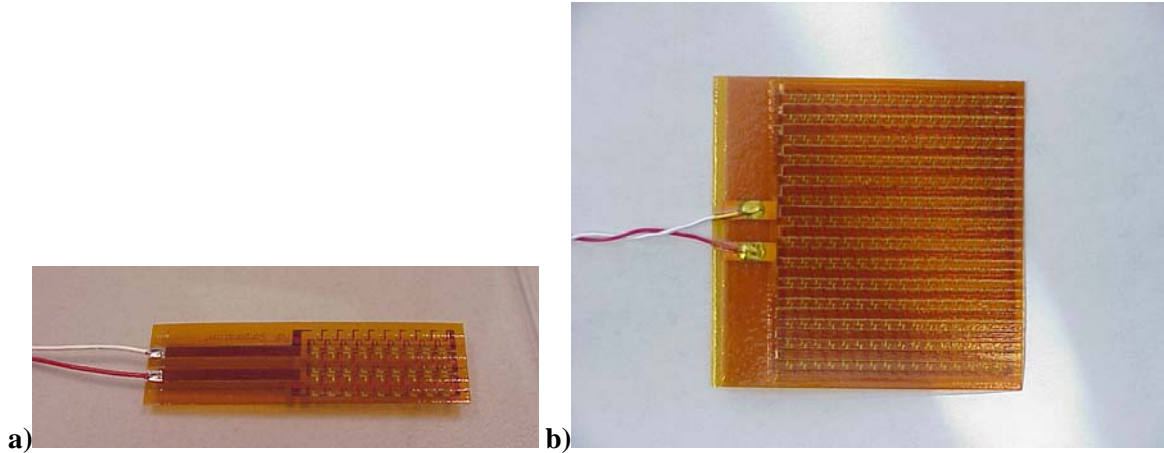
Fig. 2 Photographs of two RdF Heat Flux Sensors: a) Model 27160 (small). b) large custom-made sensor.

Experimental Setup

Three RDF 27160 sensors were attached to a 76.2 mm $\times$ 76.2 mm $\times$ 6.35 mm copper block, after which the assembly was painted black (see Fig. 3). Two Minco Products' flexible heaters were attached to the opposite side of the copper block, so its temperature could be controlled during the experiment.
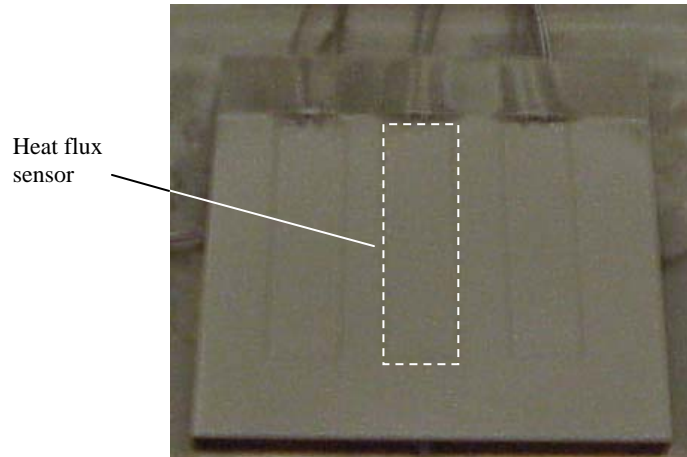
Heat flux sensor

Fig. 3 Three heat flux sensors are attached to the copper plate, then the assembly is painted black (the dash-line rectangle shows the middle heat flux sensor).

A vacuum chamber was designed and fabricated to conduct the experiment on the heat flux sensors and copper block assembly in a high vacuum environment so that heat loss through convection and conduction to the air could be eliminated. The vacuum chamber consists of a 10 in (25.4 cm) diameter cylindrical basin that is 9 in (22.9 cm) in depth with 1/8 in (0.32 cm) thick walls and bottom, capped with a 1 in (2.54 cm) thick by 12 in (30.5 cm) diameter stainless steel flange. The lid has four feedthroughs allowing for connection of thermocouples, heat flux sensors, power for the heaters, and one for the excitation voltage of the active emissivity surface that will be later tested using this test setup. The chamber is connected through a 0.5 in (1.27 cm) OD tube to the vacuum system, which consists of a turbo-molecular pump and a rough pump that are capable to sustain a pressure of 10^{-9} bar inside the chamber. This pressure is low enough to eliminate conduction losses from the heated surface to the remaining gas. Four 3/8 in (0.95 cm) threaded rods are screwed into the top flange to support the chamber when suspended inside a liquid nitrogen Dewar flask. A 1/4 in (0.64 cm) diameter Teflon rod that is 2 in (5 cm) long is used to suspend the copper block underneath the chamber lid. Figure 4 shows the assembly that consists of the chamber lid, feedthroughs, and the copper block.
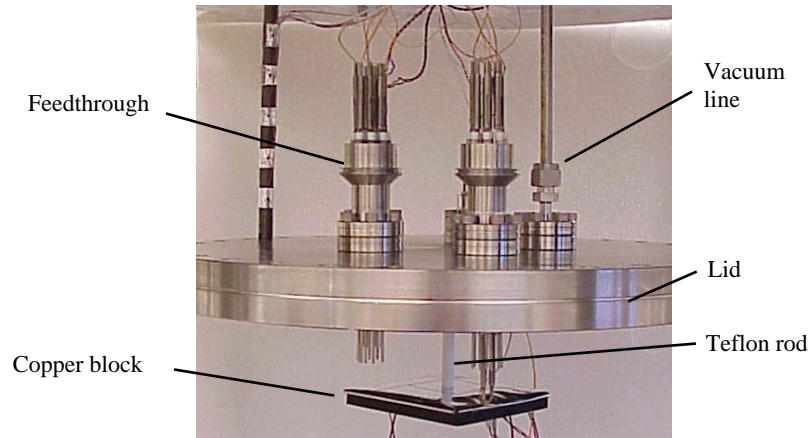
**Fig. 4 Vacuum chamber lid, feedthroughs, and copper block assembly.**

The inside of the vacuum chamber was painted black. In order to prevent the heated surface from seeing its reflection on the bottom of the chamber, a cone was fabricated and attached to the bottom of the chamber to ensure that multiple reflections occurred before the emitted radiation returns to the copper block. The heat flux gauges essentially saw a blackbody at –195 °C. Figure 5 shows a schematic of this arrangement.
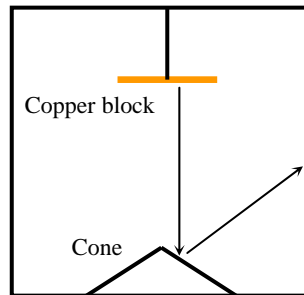
Fig. 5 Schematic of the cone position inside the chamber.

Figure 6a shows the vacuum chamber fully assembled, and Fig. 6b shows the vacuum chamber installed inside the Dewar flask. A data acquisition system was used to record temperature and heat flux sensors readings.
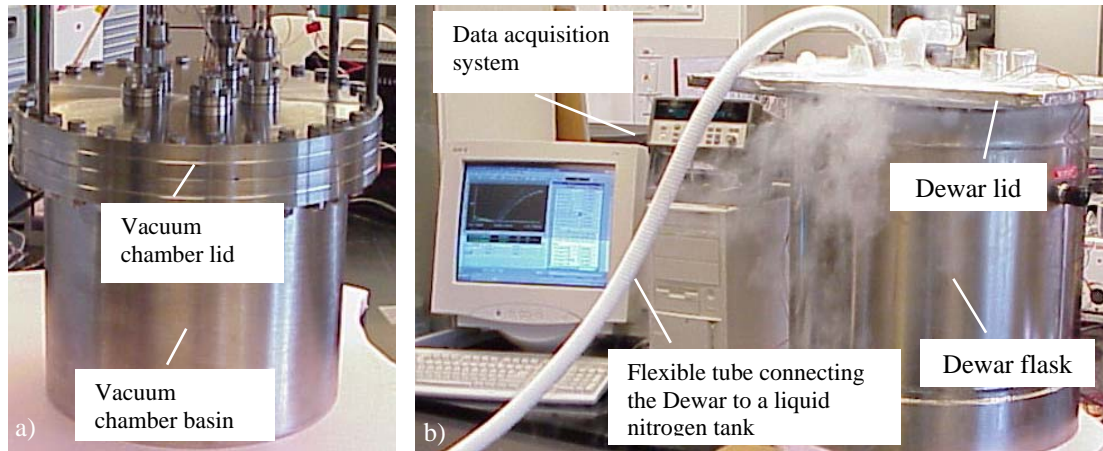
**Fig. 6 Vacuum chamber assembly and the experimental setup.**

Experimental Procedure for Testing the Black Paint

The Dewar flask was gradually charged with liquid nitrogen. Less than one hour was required for the entire vacuum chamber assembly to reach liquid nitrogen temperature (-195 °C), as indicated by the six thermocouples installed at different locations on the internal surface of the vacuum chamber (basin and lid). Electrical power was then supplied to the copper block until it reached 60°C, after which the heaters were turned off. The copper block temperature and the output of the heat flux sensors were then recorded as the copper block cooled down to -50°C over a period of 2.5 hours.

## Test Results on Black Paint

The heat flux values were obtained by dividing the measured output voltages from the heat flux sensors by their sensitivities or calibration constants (μV/(W/m^2)). The sensitivity for each sensor at a reference temperature was supplied by the manufacturer, as well as the correction factors to adjust these sensitivity values for temperature.

The heat flux as a function of surface temperature is shown in Fig. 7. We have included data obtained both from the transient test described above ("Sweep" test: heat flux and temperature data are collected as the copper block cools continually by radiation from 60°C to –50°C) and from "Step" experiments. In the "Step" experiments, a series of discrete power levels were supplied to the heaters on the copper block, and the steady-state sensor readings and substrate temperatures were recorded at each power level. We have included in Fig. 7 the heat flux that should be generated over this range of temperatures if the emissivity of the surface is 0.90, calculated using Eq. (1). The heat fluxes measured via the sweep and step experiments are in reasonable agreement with the calculated values.

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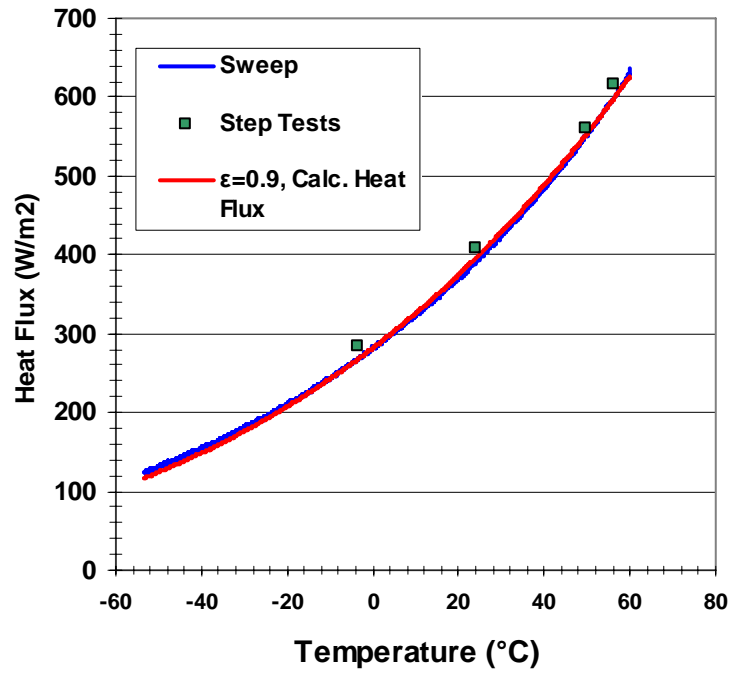
Fig. 7 Heat Flux as Function of Block Temperature.

The heat flux values, the average block temperatures, and the average chamber temperatures were then used to calculate the emissivity using Eq. (1). The resulting emissivities obtained simultaneously from three sensors mounted on the copper block are shown in Fig. 8. The emissivity values for a flat black paint are in the expected ranges of 0.85-0.95.
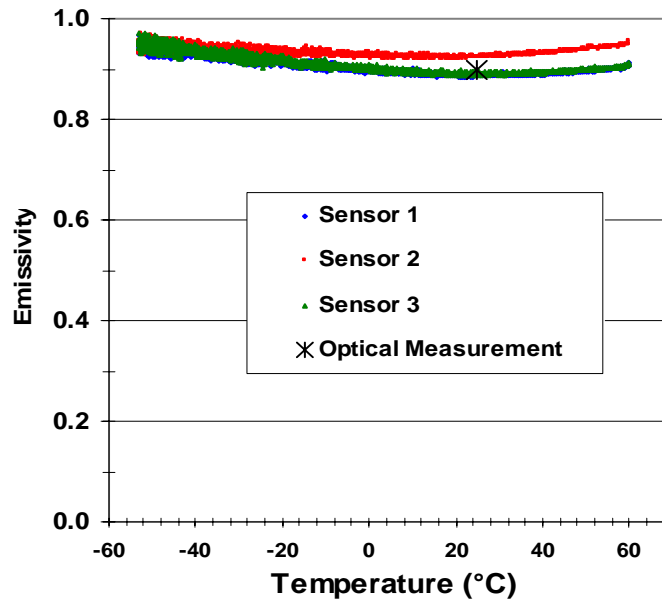
Fig. 8 Emissivities of sensors coated with black paint as functions of temperature.

The emissivity is essentially independent of temperature from about 60°C down to -50°C. The difference in reading of the three heat flux sensors is less than 5%, which is about their calibration accuracy.

In order to compare the results with an independent measurement, a 5-mil thick polyimide film (of the same material as the heat flux sensor) was painted with the same black paint used on the heat flux sensors and sent to Sheldahl Corporation for an optical measurement of its emissivity. Sheldahl uses a Lion Research Corporation emissometer to estimate total hemispherical emissivity according to industry standard, which is "Method B" in ASTM E408. The emissometer responds to broadband (3-30 microns) IR energy, and the measurement is taken at only one temperature. Sheldahl measured the emissivity of the black paint surface as 0.90 at ambient temperature. This point is plotted on the graph of emissivity with the data from the heat flux sensors.

Assembly and Testing the ESR

To demonstrate the capability of the HFB method in measurement of the rapid changes in emissivity of an ESR device, a test module incorporating a heat flux sensor and an ESR device was assembled by Sensortex Inc. Operation principle of the ESR is discussed in Biter et al.[3,4]. A schematic cross section of the test unit is shown in Fig. 9. It is built on a 76.2mm x 76.2mm x 6.35mm aluminum substrate. A large heat flux sensor was attached to the

substrate, and a thin (0.032 in or 0.813 mm) aluminum plate was epoxied on top of the heat flux sensor. The aluminum plate has a tab at one corner for attaching it to a high voltage lead. This aluminum plate serves as the high voltage side when the ESR is actuated. A 0.5-mil (12.7 μm) thick sheet of Kapton was then epoxied to the aluminum plate to serve as an electrical insulator. Finally the corners of the ESR membrane were attached on the Kapton layer, so that the membrane is suspended loosely over the Kapton insulating layer while the ESR is not actuated. In this configuration, when a ground lead is attached to the backside of the membrane (backside of the membrane is metallized and has a low emissivity) and a high voltage is applied to the lead attached to the aluminum plate, the ESR is actuated and clings tightly to the surface. This changes the heat transfer mode between the membrane and the surface beneath it from radiation to conduction. In this mode, the emissivity of the device is very close to the emissivity of the front side of the membrane.

A heater was attached on the backside of the aluminum substrate. The ESR substrate was suspended inside the vacuum chamber the same way as the copper substrate with the small heat flux sensors. The Dewar flask was filled with liquid nitrogen as before, so that the chamber reached -195°C. Heat was applied to the substrate so that it remained at a constant temperature and the ESR was allowed to radiate energy to the chamber walls. Before each test, the temperature of the substrate was raised or lowered to a desired value and allowed to become steady. The tests were started with the ESR deactivated, and then a DC voltage was applied to actuate it. Heat flux passing through the device was continuously measured by the heat flux sensor.
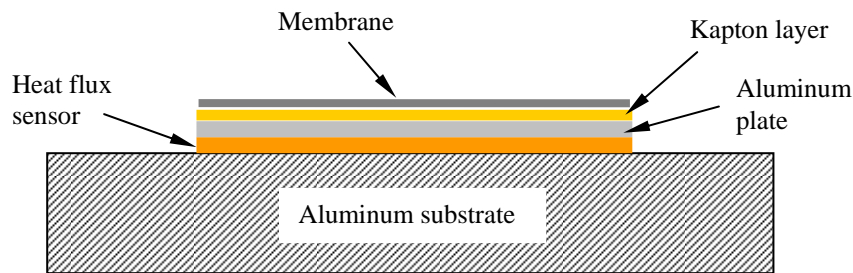

Fig. 9 Schematic of ESR on aluminum substrate (drawing is not in scale).

Test Results on ESR

Results from two tests at two different temperatures are shown in Fig. 10. When the ESR is not activated, a small gap exists between the membrane and the Kapton layer, inhibiting heat flux to the membrane and thus through the ESR. When the ESR is actuated, a sharp increase in heat flux occurs at the surface, which is a combination of the

now higher radiation being emitted by the ESR, and some residual heat as a new temperature is established near the surface. This transient portion of the heat flux dissipates in about 12 seconds, and the apparent emissivity of the surface stabilizes at a value of 0.63 higher than the device's deactivated emissivity.
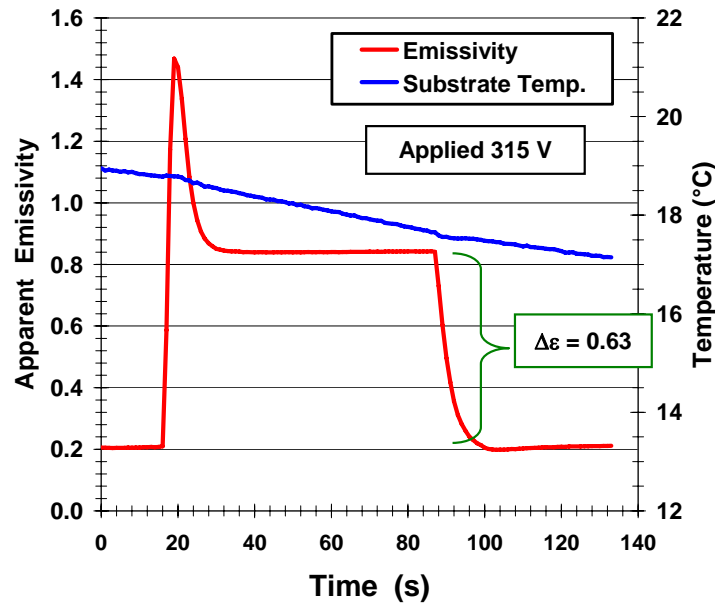
Fig. 10 Apparent emissivity and substrate temperature as functions of time during actuation (315 Volts) of ESR at 18°C

MISSE Space Test Package

In order to test the HFB emissivity measurement system and to test an active thermal control surface (ESR) in space, a module containing six HFB sensors, two ESR surfaces, and their associated electronics was designed and is being fabricated and tested. This module will be installed in MISSE-6 (Materials International Space Station Experiment), which is to be installed by a Space Shuttle crew to the exterior of the International Space Station in 2007. The MISSE package will be retrieved about a year after deployment. A schematic diagram of the module is shown in Fig. 11.
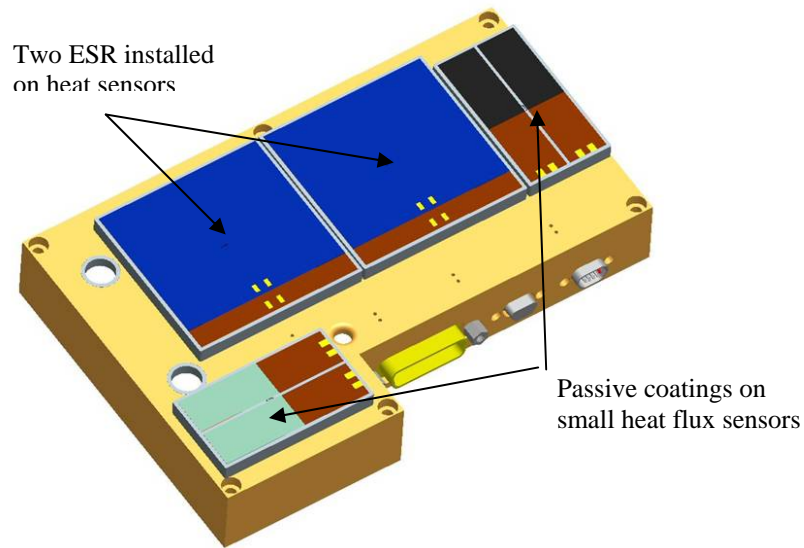
**Fig. 11 Schematic diagram of MISSE module with six HFB emissivity sensors.
Two large sensors are for testing active thermal surfaces**

Conclusion

A new method has been developed for measuring the emissivity of surfaces over a wide range of temperatures. This method employs a more direct means for determining emissivity, making it ideal for studying advanced variable emissivity coatings and structures and for deploying on spacecraft. The use of heat flux sensors allows the measurement of the emissivity of surfaces with the temporal and spatial resolutions both to evaluate coatings that can change their emissivities and to monitor the changes in emissivities of surfaces exposed to space or other harsh environments.

Acknowledgments

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